State Machines in OpenModelica

Current Status and Further Development

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Goals of this presentation

- Introduce Modelica state machines.
- Describe the implementation approach.
- Pros and cons of the current approach and further development plans.

Motivation

- Control application often consists of:
    1. Data-flow parts ↦ block diagrams
    2. System logic ↦ state machines
- Previous state machine attempts were library based (e.g., *StateGraph* and *StateGraph2* library)
- However, Library based attempts not considered to be enough powerful and convenient/safe to use
- Now, Statechart like support is available as built-in language feature

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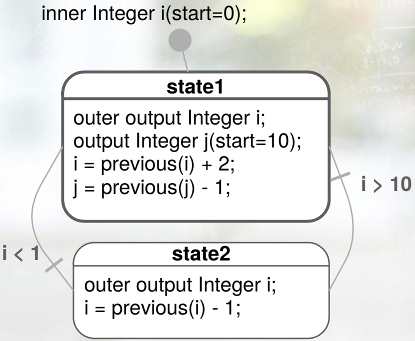
Simple Example



inner Integer i(start=0);

state1

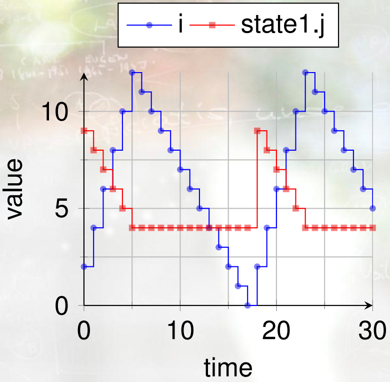
```
outer output Integer i;
output Integer j(start=10);
i = previous(i) + 2;
j = previous(j) - 1;
```

i > 10

i < 1

state2

```
outer output Integer i;
i = previous(i) - 1;
```

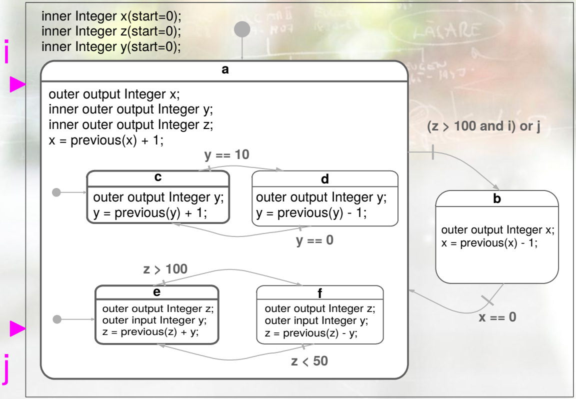


- Equations are active if corresponding *clock* ticks. Defaults to a periodic clock with $1.0\,\mathrm{s}$ sampling period.
- “`i`” is a shared variable, “`j`” is a local variable. Transitions are “*delayed*” and enter states by “*reset*”.

Simple Example: Modelica Code

```
model Simple_NoAnnotations "Simple state machine"
  inner Integer i(start=0);
  block State1
    outer output Integer i;
    output Integer j(start=10);
  equation
    i =  previous(i) + 2;
    j =  previous(j) - 1;
  end State1;
  State1 state1;
  block State2
    outer output Integer i;
  equation
    i =  previous(i) - 1;
  end State2;
  State2 state2;
equation
  transition(state1,state2,i > 10,immediate=false,
    reset=true,synchronize=false,priority=1);
  transition(state2,state1,i < 1,immediate=false,
    reset=true,synchronize=false, priority=1);
  initialState(state1);
end Simple_NoAnnotations;
```

M&R-Example: Hierarchical and Parallel Composition



inner Integer x(start=0);
inner Integer z(start=0);
inner Integer y(start=0);

i

j

a

outer output Integer x;
inner outer output Integer y;
inner outer output Integer z;
x = previous(x) + 1;

y == 10

c

outer output Integer y;
y = previous(y) + 1;

d

outer output Integer y;
y = previous(y) - 1;

y == 0

z > 100

e

outer output Integer z;
outer input Integer y;
z = previous(z) + y;

f

outer output Integer z;
outer input Integer y;
z = previous(z) - y;

z < 50

(z > 100 and i) or j

b

outer output Integer x;
x = previous(x) - 1;

x == 0

Semantics of Modelica state machines (and example above) inspired by

Florence Maraninchi & Yann Rémond. Mode-Automata: a new domain-specific construct for the development of safe critical systems . *Science of Computer Programming*, 46:219–254, 2003.

and by Marc Pouzet's language ***Lucid Synchrone 3.0***.

Summary of intuitive semantics

Modelica state machines:

- Extend on the synchronous language extension.
- Support *hierarchic* and *parallel composition* of states, *immediate* (strong) and *delayed* (weak) transitions, entering a state with *reset* or *resume* of internal state memory (enter by history).
- *States* are instances of ordinary blocks with data-flow equations.
- Block instances become states if they appear as argument in `transition(..)` or `initialState(..)` operators.

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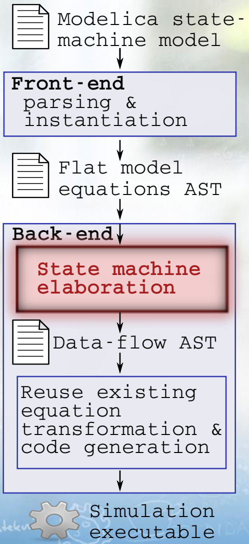
Approach used for the OpenModelica Prototype



Modelica state-machine model

Front-end
parsing & instantiation

Flat model equations AST

Back-end

State machine elaboration

Data-flow AST

Reuse existing equation transformation & code generation

Simulation executable

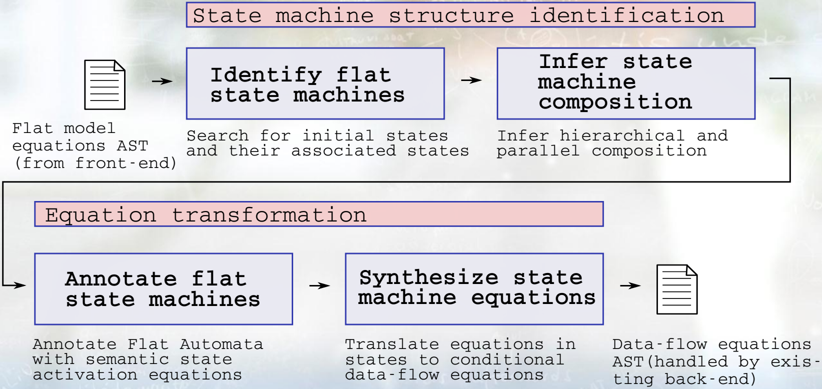
State machine elaboration

State machine control structures are translated to basic data-flow equations (*AST transformation*).

Inspired by (but simultaneously quite different to)

Jean-Louis Colaço, Bruno Pagano & Marc Pouzet. A Conservative Extension of Synchronous Data-flow with State Machines . In *Proceedings of the 5th ACM International Conference on Embedded Software*, 2005.

State-Machine Elaboration



State machine structure identification

Flat model equations AST (from front-end)

Identify flat state machines

Search for initial states and their associated states

Infer state machine composition

Infer hierarchical and parallel composition

Equation transformation

Annotate flat state machines

Annotate Flat Automata with semantic state activation equations

Synthesize state machine equations

Translate equations in states to conditional data-flow equations

Data-flow equations AST (handled by existing back-end)

M&R-Example: Information Available in Flat Model AST

```
class MRExample "Flattened example from slide 6"
  input Boolean i = true, j = false; // assume constant SM inputs
  inner Integer x(start = 0), z(start = 0), y(start = 0);
  inner outer output Integer a.y = y, a.z = z;
  outer output Integer a.x = x, a.c.y = a.y, a.d.y = a.y;
  outer output Integer a.e.z = a.z, a.f.z = a.z, b.x = x;
equation
  initialState(a);
  initialState(a.e);
  initialState(a.c);
  transition(a.e, a.f, a.z > 100, false, true, false, 1);
  transition(a.f, a.e, a.z < 50, false, true, false, 1);
  transition(a.c, a.d, a.y == 10, false, true, false, 1);
  transition(a.d, a.c, a.y == 0, false, true, false, 1);
  transition(a, b, z > 100 and i or j, false, true, false, 1);
  transition(b, a, x == 0, false, false, false, 1);
  a.c.y = 1 + previous(a.c.y);
  a.d.y = -1 + previous(a.d.y);
  a.e.z = previous(a.e.z) + a.y;
  a.f.z = previous(a.f.z) - a.y;
  a.x = 1 + previous(a.x);
  b.x = -1 + previous(b.x);
end MRExample;
```

M&R-Example: State machine structure identification

1. Identify flat state machines by computing transitive closure over transition relations:

Flat SM	**States**
`sm0f.a`	`a, b`
`sm0f.a.c`	`a.c, a.d`
`sm0f.a.e`	`a.e, a.f`

2. Infer state machine composition (*state refinements*) from the list of flat state machines:

$$R_{\mathtt{sm0f.a}}(\mathtt{a} \mapsto \{R_{\mathtt{sm0f.a.c}}(\mathtt{a.c}, \mathtt{a.d}) || R_{\mathtt{sm0f.a.e}}(\mathtt{a.e}, \mathtt{a.f})\}, \mathtt{b})$$

M&R-Example: Annotate flat state machines

Abridged and simplified activation equations for `smOf.a`:

```
constant Integer smOf.a.tTo[2] = {2,1}; // transition "to"
constant Integer smOf.a.tFrom[2] = {1,2}; // transition "from"
Boolean smOf.a.init(start=true) = false; // false except start value
// Ensure SM reset at first clock tick
Boolean smOf.a.reset := previous(smOf.a.init);
// delayed transitions
Boolean smOf.a.c[2] :=
  {previous(z > 100 and i or j), previous(x == 0)};
// State update starts from previous active state
Integer smOf.a.selectedState :=
  if smOf.a.reset then 1 else previous(activeState);
// If several can fire, the highest priority is chosen:
Integer smOf.a.fired := max({
  if (smOf.a.tFrom[2] == smOf.a.selectedState
    then smOf.a.c[2] else false) then 2 else 0,
  if (if smOf.a.tFrom[1] == smOf.a.selectedState
    then smOf.a.c[1] else false) then 1 else 0)}
// A reset forces the activeState to be the initial state
Integer smOf.a.activeState = if smOf.a.reset then 1
  else (if smOf.a.fired > 0 then smOf.a.tTo[smOf.a.fired]
    else smOf.a.selectedState);
```

M&R-Example: Synthesize state machine equations

1. Merge activation equation annotations of flat state machines and add them to the flat equation AST.
2. Translate equations in states to conditional data-flow equations, e.g.,:

```
x := if smOf.a.activeState == 1
  then previous(x) + 1 else previous(x) - 1;
```

Note: Current prototype uses a workaround due to clocked synchronous features not being implemented yet and wraps all SM related equations in:

```
when sample(0, 1.0) then
  x := if smOf.a.activeState == 1
    then pre(x) + 1 else pre(x) - 1;
end when;
```

Current implementation pros and cons

Pros:

- Implementation can be added to OMC in a modular manner (as pre-optimization module in the back-end).
- Remaining modules for equation sorting, optimization, and code generation can be used without modification.

Cons:

- State machine structure identification from the flat model AST requires costly elaboration.
- Activation equations lead to many new equations and variables (costly in terms of performance and memory efficiency).
- Extensive symbolic transformation complicates traceability and leads to error messages that are not helpful.

Outlook

- First state machine prototype (partial implementation of complete semantics, about 3000 LoC) will be merged into the main development branch in the coming weeks.
- In parallel, ongoing implementation of clocked synchronous constructs in OpenModelica ongoing at FH Bielefeld. Currently, equation partitioning achieved.
- Future challenges: Complete implementation, *efficiency* of translation process and generated code, *adequacy* of translation approach, *traceability*, *error messages*, *debugging*, *hybrid state machines* . . .

Specialities of the state machine semantics

Modelica state machine:

- All variables in the state machine are on the same clock — this is in contrast to to the Mode-Automata design paradigms where modes (≡ states) should behave like clocks.
- Consequently, variables of inactive states are accessible/readable whenever the clock of the state machine ticks.
- “Shared” variables are realized by instance hierarchy name lookup of “**`inner`**” declarations with merging of variable definitions that correspond to “**`outer output`**” declarations of (mutual exclusive) states. They are kept constant if no defining state is active.
- Non-normative specification text suggests the use of “**`inner outer output`**” for intermediate instance levels of “shared” variables.
- “Immediate” and “delayed” transitions are significant different to Lucid Synchrone: All transitions are “immediate”, “delayed” transitions are “immediate” transitions wrapped in a **`previous(..)`**.
- A “reset” will enforce the initial state to be active even if a transition from the initial state could fire immediately.